OPERATIONAL IMPROVEMENTS OF
TRACKING AND DATA RELAY SATELLITE (TDRS)
POSTMANEUVER SOLUTIONS*

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ABSTRACT

The Flight Dynamics Facility (FDF) at the Goddard Space Flight Center (GSFC) performs Tracking and Data Relay Satellite (TDRS) orbit determination for the Space Network (SN) and for TDRS System (TDRSS) users. The Terra [Earth Observing System (EOS) AM−1] satellite requires TDRS ephemerides with 3σ accuracies of 75 meters in position and 5.5 millimeters per second in velocity predicted over 1 day onboard, including updates by 4.5 hours after TDRS maneuvers. This analysis reviews the accuracy of 209 postmaneuver orbit solutions for 6 TDRSs since February 1998.

The FDF constrains the TDRS orbital plane through input covariances in postmaneuver orbit solutions. The FDF started using this technique following in–plane TDRS maneuvers in 1998; this improved the average 42–hour prediction accuracy from 109 to 58 meters in 1998. Nevertheless, the Terra 75–meter requirement was still not always met.

Four techniques that have been used to further improve accuracy include requesting tailored tracking data, applying a range bias, fine tuning plane constraints, and changing data weights. Bilateration Ranging Transponder System (BRTS) tracking events have been assessed based on differences in tracking data generation and performance of one antenna service or ground tracking site compared with another. Because of observational geometry, the Alice Springs, Australia, site is preferred over the American Samoa site for the TDRSs near 170 degrees west longitude. For legacy TDRSs, Single Access (SA) Doppler data yields better results than Multiple Access (MA) Doppler data. These differences in tracking data performance lead to tracking data requests that are tailored for best results.

The three other techniques have also reduced both the along−track and cross−track errors. An optimal range bias was determined after each TDRS maneuver to help in assessing what bias should be applied for the next maneuver of that TDRS. Plane constraints have been tightened for all TDRSs to provide accuracy improvements, especially for the TDRSs with the lowest

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orbital inclinations. Data weight changes have helped achieve improved results and more stable use of Doppler data.

Using these procedures, the FDF meets the Terra requirement 99.5 percent of the time with an average 42–hour prediction error of 44.6 meters and a standard deviation of 19.5 meters. The FDF continues to work toward further improvements so that Terra's 3σ accuracy requirements will be met. Because of large variations in the optimal applied range biases, additional updates for TDRS–4 may be needed to meet Terra accuracy requirements. Modeling upgrades for spacecraft area and for different antenna biases may further improve results.

1. INTRODUCTION

This paper evaluates Tracking and Data Relay Satellite (TDRS) postmaneuver solution accuracy and several techniques employed to improve accuracy. The main reason for seeking improved TDRS accuracy is to ensure that the FDF will meet the accuracy requirement for the Terra [Earth Observing System (EOS) AM–1] satellite. Flight Dynamics Facility (FDF) personnel at the Goddard Space Flight Center (GSFC) provide TDRS state vectors to the National Aeronautics and Space Administration (NASA) Space Network (SN) and to TDRS System (TDRSS) users such as Terra for operational support. The accuracy of the TDRS ephemerides is the major contributor to the accuracy of the Terra ephemeris.

The Terra Project has 3σ requirements for TDRS ephemerides of 75 meters and 5.5 millimeters per second predicted over 1 day onboard (Reference 1), which is 1.5 days from the end of a daily operational solution arc. Driving this requirement is the Terra Multi–angle Imaging Spectroradiometer (MISR) instrument, which requires a 3σ position accuracy of 25 meters for Terra. The TDRS ephemeris for Terra is required to be updated within 4.5 hours after a TDRS maneuver (Reference 2), and it is typically based on up to 4 hours of tracking data.

This paper is a follow–on study to a constrained–plane analysis that began before the Terra launch in an effort to improve success in meeting the Terra requirement after TDRS maneuvers (Reference 3). Orbital planes have been constrained operationally for orbit solutions after TDRS maneuvers since 1998, improving the average 42–hour prediction accuracy from 109 to 58 meters. However, work still remained to meet the Terra 75–meter requirement at the 3σ level.

Discussed below are background information and a description of the techniques that have been used to improve TDRS accuracy. The results of applying the various techniques are then presented, followed by a summary and recommendations.

2. BACKGROUND

A description of the orbit determination process and study sample follows.

The FDF uses the Goddard Trajectory Determination System (GTDS) to perform batch–least–squares solutions operationally with Bilateration Ranging Transponder System (BRTS) tracking data. Postmaneuver solutions use both BRTS range and Doppler observations, and apply an average coefficient of reflectivity (C_R) for solar radiation. GTDS gives the analyst the capability to constrain the orbital plane through input covariances. The constrained–plane orbital solution method was used for each short–arc solution in the sample. Table 1 lists key GTDS modeling options. A delay of –54.7 nanoseconds was applied for the BRTS at American Samoa (AMS) after April 10, 1998. This delay was changed to –78.7 nanoseconds for new troposphere modeling and TDRS antenna offsets on September 2, 1999.

Table 1. TDRS Postmaneuver Modeling Options

Parameter	Value
Data arc length	4 hours after maneuver window
Geopotential model	70x70 JGM–2 truncated to 8x8, with constant J_2 term over time
Noncentral bodies	Sun and Moon
Coordinate integration reference system	Mean of J2000.0
Integration type (step size)	Cowell fixed step (300 seconds)
Coordinate integration system	Keplerian
Covariance constraints	1 or $3x10^{-13}$ degree^2 or less for both inclination and right ascension of ascending node (see section 4C)
Estimated parameters	State vector
Tropospheric refraction model	Saastamoinen/Niell/Radomski model for TDRSS refractive delays (Reference 4)
Solar reflectivity coefficient (C_R) (applied)	Between 1.35 and 1.47, or for TDRS–8, between 0.97 and 1.03
Satellite geometry model	Sphere with cross–sectional area of 40 or, for TDRS–8, 65.65 meters^2
Timing delays applied through GTDS	–78.7 nanoseconds for American Samoa BRTS
Tracking data types	S–band BRTS range and Doppler
Applied range bias	See sections 3B and 4B
Polar Motion	On
Tides	Off
Antenna offsets	GTDS 99.01 defaults
Shadow modeling	Conical umbra/penumbra

This study includes 209 maneuvers during the period from February 4, 1998, to August 28, 2003, for 6 TDRSs for which FDF personnel performed postmaneuver orbit solutions with BRTS tracking data. TDRS−1, −4, −5, −6, −7 and −8, which had data from two BRTS sites, were selected for study. Because TDRS−3 is supported with only one BRTS and with Tracking, Telemetry, and Command data from Guam (Reference 5) and not with two BRTS, it was omitted from this study. Reference 6 gives an excellent overview of BRTS and the geosynchronous TDRSs. Current longitude, inclination, and other information on each TDRS can be found at http://fdf.gsfc.nasa.gov, which is available for authorized users. Figure 1 displays this map with the longitudinal box for each TDRS, the White Sands Complex (WSC), and the three other BRTS sites.

Maximum prediction errors were evaluated over 42–hour reference solution spans with BRTS range data. These solutions typically estimate C_R and a range bias with unconstrained orbital planes if there were no momentum unloads. Before GTDS momentum unload modeling began, definitive BRTS−based solutions were accurate to ~100 m (3σ) (References 7 and 8). With momentum unload modeling, definitive 3σ accuracies have improved to approximately 60 meters, based on overlapping consistencies.

Previous analysis (Reference 9) has shown that momentum unload modeling is a necessary component of TDRS modeling for Terra support. The first TDRS momentum unload modeling study by the FDF showed that when the positional accuracy requirement (75 meters, 3σ) was met, the velocity accuracy requirement (5.5 millimeters per second, 3σ) was also met (Reference 9). Therefore, this study primarily addresses the FDF's ability to meet the positional accuracy requirement, even though the velocity requirement is also assessed in daily ephemeris comparisons.

3. TECHNIQUES

Four techniques that have been used to improve accuracy are 1) requesting tailored tracking data, 2) applying a range bias, 3) fine tuning plane constraints, and 4) changing data weights. These techniques are described below.

A. Tailored Tracking

Before each TDRS maneuver, the FDF sends a request for tracking events after the maneuver. The objective of tailored tracking is to request the subset of available tracking services that is most likely to yield the most accurate results. BRTS tracking events are requested, scheduled, and assessed based on differences in tracking data generation and preferential performance of one transponder or service type over another. The viewing geometry of a BRTS site is also a criterion by which tailored tracking is requested.

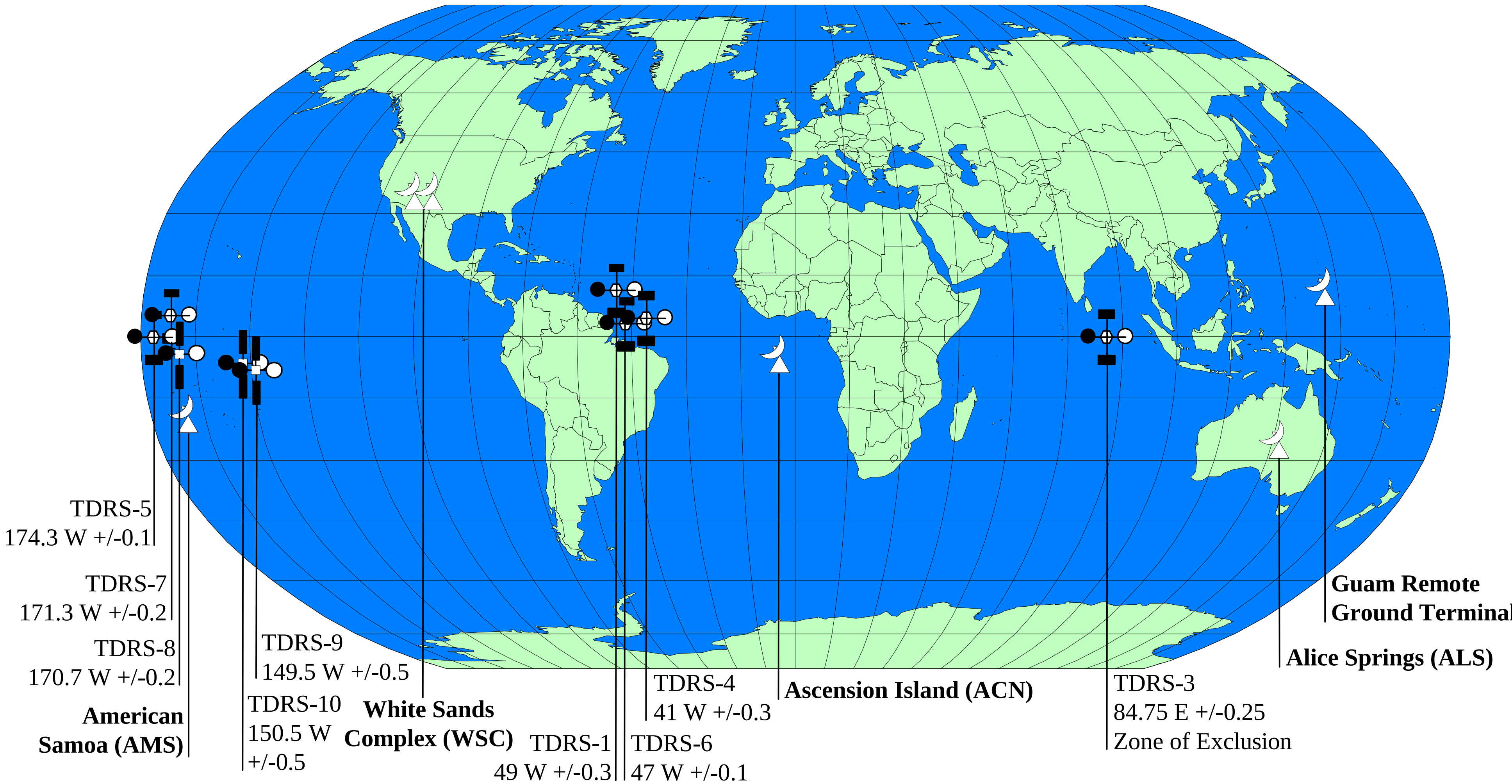

Figure 1. TDRS Locations, Space-to-Ground-Link Terminals, and BRTS as of February 2003

Geometry Selection

The BRTS site at American Samoa (AMS) is at a longitude that is nearly equal to the TDRS−West longitude (Figure 1), so less diverse geometry is achievable with AMS than with the BRTS located at Alice Springs, Australia (ALS). Therefore, ALS is preferred over AMS for the TDRSs (TDRS–5, –7, and –8) near 170 degrees west longitude.

Service Type and Transponder Selection

Another tracking data criterion is the BRTS service type. For the legacy TDRSs (1 through 7), Multiple Access (MA) and Single Access (SA) events have different formulations of Doppler data, but their range data formulations are identical (References 10 and 11). MA data is always S−band, and the SA data used with BRTS tracking is also S−band only. TDRS−1, −6, or –7 were normally supported during the study period by an antenna that only provides SA services.

BRTS range data is coherent two−way [Space−to−Ground−Link−Terminal (SGLT)−to−TDRS−to−BRTS and BRTS−to−TDRS−to−SGLT]. For the WSC BRTS, the range data are all on essentially the same leg (SGLT−to−TDRS), because the WSC BRTS transponder is located near the SGLT. For the remote BRTS transponders, the range data have two very different legs, but the first leg is always SGLT−to−TDRS.

Doppler statistics from FDF Tracking Support Services repeatedly showed smaller residuals and standard deviations with remote MA than with remote SA data. The data from the second Ascension Island site (AC2J) also looked better than data from the first site (ACNJ). Because the cleaner statistics looked more appealing, the initial tailored tracking requests preferred MA on the remote sites and AC2J data over ACNJ data. Antenna size and data rates (Figure 2 from http://nmsp.gsfc.nasa.gov/tdrss/scraft.html and Reference 12), however, favor SA data over MA data. The MA and SA data for the WSC BRTS transponders looked similar.

Because of differences in the frequency conversion algorithms aboard the legacy TDRSs and on the ground, the MA Doppler measurements are more sensitive to the relative motion between the TDRS and remote BRTS sites than that between the TDRS and the WSC BRTS site. In contrast, the SA Doppler data is more equally sensitive to both legs than is the MA Doppler data.[1] To achieve a balance in the sensitivity of both Doppler and range data, only SA data is requested for the legacy TDRSs. For TDRS−8, however, the S−band MA and SA Doppler data conversion algorithms are identical. As a result, either SA or MA data can be used for TDRS–8 after maneuvers.

[1] S. Hendry, private communication, 2000

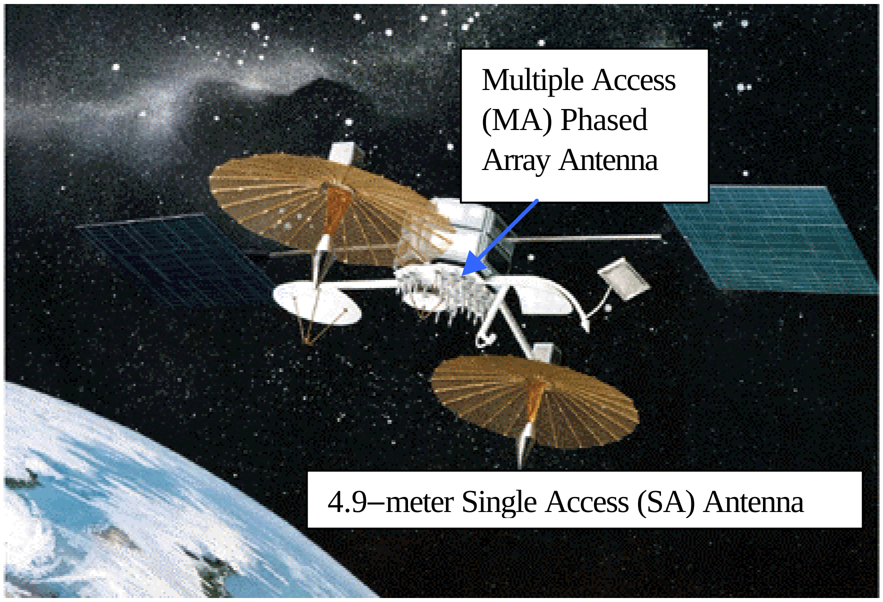

Figure 2. Legacy TDRS MA and SA Antennas

B. Applied Range Biases

In this paper, range bias refers to a composite range bias including the SGLT, the TDRS, and the two BRTS transponders. No range biases were applied initially in orbit solutions when range biases were less than 10 meters (Reference 3). At that time, the average TDRS−1, −5 and −6 range biases were between 0 and 1 meter, and the average TDRS−4 and −7 range biases were 6 and −6 meters, respectively.

An optimal range bias is currently determined after each TDRS maneuver to help assess the bias to be applied for the next maneuver of the same TDRS. Because of plane constraints, the main postmaneuver solution error over 42 hours is usually in the along–track direction. The range bias is adjusted based on a maximum along–track position difference near the end of the ephemeris comparison span to reduce the along–track error. A range bias that yields a maximum along–track difference of 30 meters or less is called an optimal range bias. An average of optimal range biases is used for the applied range bias after the next maneuver. The optimal range bias is independent of range biases estimated in routine solutions for at least two reasons: 1) The BRTS service type is usually different (SA instead of MA) and has different range biases, and 2) Doppler data is used in short–arc solutions but not in routine solutions.

C. Plane Constraints

Orbital planes have been constrained operationally for orbit solutions after TDRS maneuvers since 1998 (Reference 3). At that time, this technique improved the average 42–hour prediction accuracy by over 50 meters by reducing both the cross–track and along–track errors. The covariances used in the plane constraint analysis were 1×10^{-12} degrees^2. This technique has also been applied to other missions with favorable results (Reference 13). Tighter covariances have been used in this study in an attempt to improve TDRS accuracies.

D. Data Weights

In terms of the percent of tracking data accepted, range data dominates Doppler data by an average of 24 percent in postmaneuver solutions. When the TDRS−5 postmaneuver solution weighted root–mean–square (WRMS) was higher than 1.0 and the Doppler data use was below ~60 percent, σ–multiplier or data weight changes for both range and Doppler data were made to achieve a more stable use of Doppler data and more accurate solutions. Reference 14 describes similar improvement with ground–based tracking data for TDRSs.

4. RESULTS OF 4-HOUR POSTMANEUVER SOLUTIONS

The discussion will first focus on tailored tracking results, followed by plane constraint adjustments, applied range biases, and changed data weights. Then overall results are presented.

A. Tailored Tracking

Geometry Selection

With four exceptions, all maneuvers after June 23, 1998, were supported with tailored tracking. The sub–satellite point for TDRS–7 is at the same longitude as the AMS transponder but is 55 degrees away from ALS. TDRS−7 had results about 50 meters worse when data from AMS was used compared with when data from ALS was used. Therefore, ALS data is preferred over AMS data.

Service Type and Transponder Selection

The 4–hour solutions for TDRS−7 always agreed with the 42–hour reference solutions within 75 meters. These 4–hour solutions usually only had SA data.

For TDRS−1, −5 and −7, SA data from remote BRTS sites (ACNJ, AC2J, AMS or ALS) appeared to help 4–hour solutions more than MA data from the remote BRTS sites. The TDRS−5 results were poorest when using only MA data, whether from ALS or AMS. Figure 3 displays results for these TDRSs as a function of the percent of all data at a remote BRTS site that was SA data. While some intermediate results are mixed, a clear trend is apparent between no SA data and all SA data. Because the range data algorithms for SA and MA are the same, it appears that it is more important to have Doppler data for both tracking

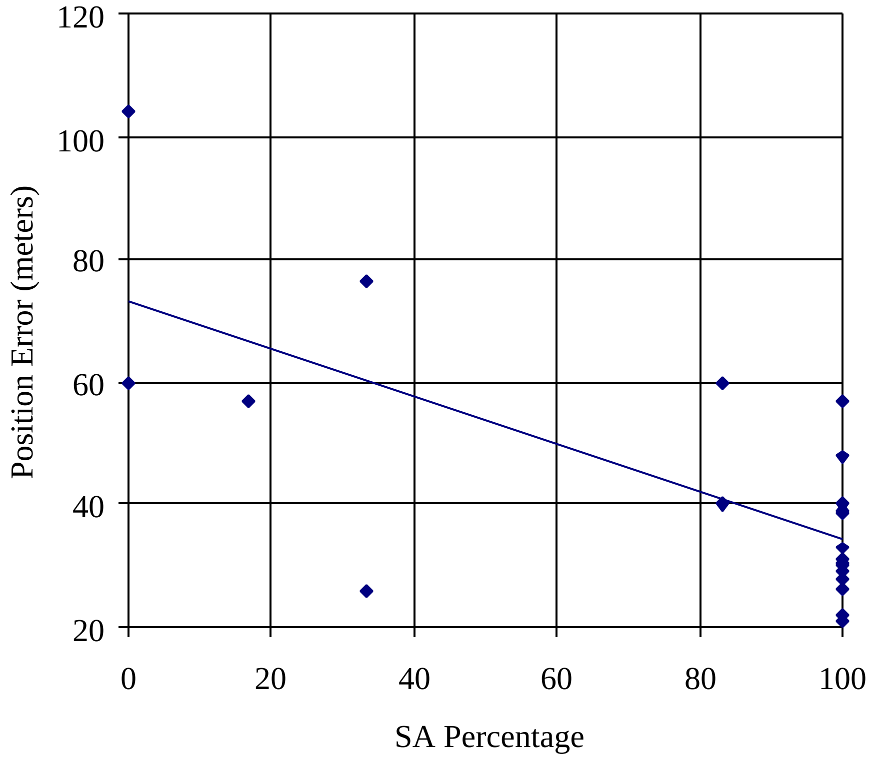

Figure 3. Postmaneuver Error and Remote BRTS SA Data

legs representing the geometry and dynamics exhibited in the remote range data, rather than to focus on the remote leg. Therefore, SA data is preferred over MA data, especially for remote BRTS sites.

The results for one TDRS−4 maneuver were over 100 meters for a solution where only one of the six WSC BRTS events was an SA event. Otherwise, there was no clear early preference of SA or MA data for TDRS−4, with two cases above 75 meters and three below. However, a spread of 6 meters or more between MA and SA range data was commonly noted for TDRS−4. Because of this large disparity, a request was made to only schedule MA events for routine daily support for TDRS−4. After the switch was fully made on February 2, 2000, TDRS−4 routine daily accuracies improved by 12 meters on average.

Performance generally improves with this tailored tracking for both sites and services. The accuracy improvement is not monotonic with increasing amounts of SA data, but the best results were consistently achieved when the scheme described above was followed.

Recent postmaneuver results have encouraged a further tailoring of tracking data requests based on the TDRS onboard antennas. To avoid disparities in range bias between different SA antennas, all SA data after a maneuver could use the same antenna (SA1 or SA2). However, scheduling priorities make it unlikely that a particular SA antenna is available for all tracking for 4 hours after a maneuver. Because worse results seem to occur when the two antennas are not scheduled in an equal proportion, requests for equally mixed use of SA1 and SA2 antennas began for TDRSs with the TDRS−5 maneuver on July 22, 2003.

Early in the analysis, the FDF discovered that TDRS−1 solutions were 8 meters better on average with both ACNJ and AC2J data, rather than with only AC2J data, contrary to the initial expectation based on better statistics for AC2J. Thereafter, no discrimination was made between ACNJ and AC2J for tracking requests. Because of hardware problems, TDRS−4 and −6 solutions have not had the benefit of ACNJ data in their recent postmaneuver solutions.

B. Applied Range Biases

Early in the study period, the 4–hour solutions for TDRS−4 and −7 needed applied biases to meet the 75–meter Terra requirement. Eventually, 4–hour solutions for TDRS−5 and –6 also needed applied biases as the bias drifted upward from near 0 meters. Range biases are currently applied for all TDRSs in 4–hour solutions.

Because of significantly different range biases and the lack of a GTDS feature to separate them easily, MA data has normally been requested for routine tracking data for all TDRSs. This began with TDRS−4 and –6 in the first half of the year 2000. Furthermore, SA data was requested exclusively for the first 4 hours after a maneuver. Therefore, a separate analysis was needed to determine an optimal SA bias to apply after maneuvers. The optimal range bias was determined by adjusting the range bias until a minimal level (30 meters or less) of maximum along–track differences occurred in the ephemeris comparison with the ephemeris based on the 42–hour reference solution. The minimal along–track differences generally persist with range values varying by a few meters from the optimal range bias. This allows an average optimal bias to work well for more than one maneuver, even when the optimal range bias changed by a few meters. An optimal bias worked better when averaged over more than just the last five or six maneuvers for TDRS−4 and −8, both of which had some changes in the optimal biases at the 10–meter level.

C. Plane Constraints

Sometimes covariances of 10^{-12} degree^2 did not constrain the plane tightly enough, and cross–track errors were significant (over 30 meters). At other times, covariances of 10^{-14} degree^2 constrained the plane too tightly when there was an observed plane change of over 30 meters. A plane constraint of $3x10^{-13}$ degree^2 gave better results on average for most TDRSs. The plane constraint often had a direct effect on the total error.

A constraint of $1x10^{-13}$ degree^2 gave better results for TDRS−5 in five cases when the plane constraint made a significant difference. Similar results were seen for at least three cases for

TDRS−6 in late 1999 and in early 2000. It seems significant that the tighter plane constraints worked better for the TDRSs with the lowest orbital inclinations. It is more difficult for a 4−hour solution to detect latitudinal motion with a small inclination than with a larger inclination.

It was confirmed that the optimal range bias, which primarily affects the along−track position, functions largely independently of the degree of plane constraint, which mainly affects the cross−track position.

The standard deviation of the geocentric z–position from the final state estimation in GTDS for a short−arc solution was found to strongly indicate actual accuracy of the solution plane when the standard deviation was above the 20−meter level.

Considering the latitude range of 4−hour solution arcs to anticipate different responses to a single plane constraint did not reveal any trends.

D. Data Weights

When the 1− and 2−hour postmaneuver solution WRMSs were high (between 1.1 and 3.4), data weight changes usually improved results while allowing for at least 60 percent use of Doppler data.

These high WRMS conditions started for TDRS−5 in December 2002. Initial attempts reduced the σ−multiplier from the default of 3.0 to levels as low as 2.0. The resulting WRMS and use of Doppler data were somewhat unpredictable, and the σ−multiplier that yielded more typical WRMS values, as well as high use of Doppler data, varied with each maneuver. After three consecutive TDRS−5 maneuvers had high WRMSs and the manually–tuned σ−multipliers varied from 2.46 to 2.83, data weight changes for the range and Doppler data were successfully tried and then implemented. The data weight changes were used with better results than the maneuver–specific σ−multipliers on two maneuvers, and yielded good results on two more maneuvers. The data weight changes had a poor result (91 meters) for a fifth maneuver.

Application of the above four techniques generally reduced both along–track and cross–track errors.

E. Overall Results

Figure 4 displays a 5.5−year history of TDRS postmaneuver errors. The position error of the 4−hour solutions is estimated from the corresponding 42−hour reference solutions. Results for TDRS−1, −4, −5, −6, −7 and −8 (TD1, TD4, … TD8 in Figure 4) are listed chronologically by TDRS from left to right. The TDRS−1 point with an arrow represents a point off scale at 180 meters when only the remote BRTS site was scheduled. The TDRS−8 point with an arrow represents a point off scale at 324 meters when a pitch unload occurred 2 hours after the maneuver and was not modeled. This was a coincidence of two unusual events. Since then, pitch unload calibration for TDRS−8 has been performed, resulting in 1.5–day prediction errors that are consistently below 50 meters. Except for TDRS−8, which only has data after April 2002, a general improvement with time is visible in Figure 4. This improvement is attributed to a refinement of procedures over time. When applicable, early operational results were replaced with results from the constrained plane analysis.

The 31 cases in Figure 4 that had position error results over 75 meters have been reviewed. Most of these cases were early in the study period. Upon review, 13 cases already used current procedures. For four cases the current procedures were applied and yielded improved results in Figure 5. The other 14 cases, for which the current procedures were not or could not be applied, were omitted from the next stage of the analysis, the results of which are presented in Figure 5. The reasons for omitting the data are:

- Four cases were omitted because tailored tracking data was not available. In two cases, there were a majority of MA events; one case contained an AMS event; and the TDRS−1 single BRTS site case referred to earlier was omitted.
- Six cases were omitted because a continual use of plane constraints for TDRS−5 and −6 induced cross–track errors. Since early 2000, plane constraints are typically only used near momentum unloads and after maneuvers.
- Three cases were omitted because of a momentum unload near a maneuver. The TDRS−8 pitch unload referred to earlier was omitted. Also, one TDRS−5 case had a roll/yaw unload in the postmaneuver reference solution in June 1998, before momentum unload modeling was used operationally. Finally, a TDRS–4 case was omitted because of a pitch unload in a premaneuver solution that resulted in poor plane modeling in a solution in April 1999. Since that time, momentum unload modeling has been improved.
- In October 1998, one case for TDRS−4 occurred before range biases were applied.

With current procedures, the average error for the 195 postmaneuver solutions included in Figure 5 is 44.6 meters with a standard deviation of 19.5 meters for 42 hours after maneuvers.

Figure 6 is similar to Figure 5, except that the 42−hour results over 75 meters were replaced with results over the corresponding Terra comparison time span ending at 2100 Greenwich Mean Time (GMT), which resulted in predicted spans between approximately 20 and 42 hours. Out of 195 cases, 194 met the Terra requirement. The one TDRS−4 case above 75 meters was good for 33 hours after the maneuver, but it would have been used by Terra until over 38 hours after the maneuver.

5. SUMMARY AND RECOMMENDATIONS

Using the current procedures, the average error for 195 postmaneuver solutions was 44.6 meters with a standard deviation of 19.5 meters for 42 hours after maneuvers. This is a significant improvement over the 58−meter average error in the original constrained

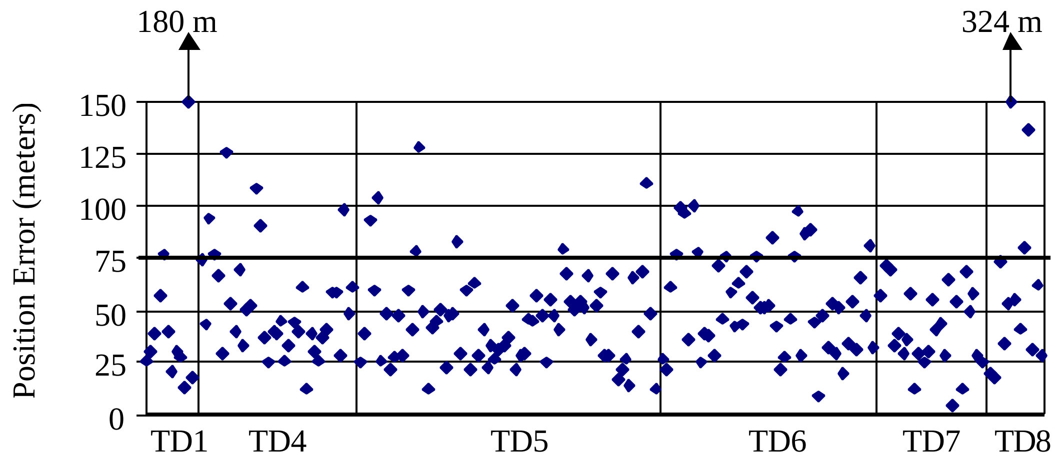

Figure 4. TDRS 42-Hour Postmaneuver Errors: 5.5-Year History

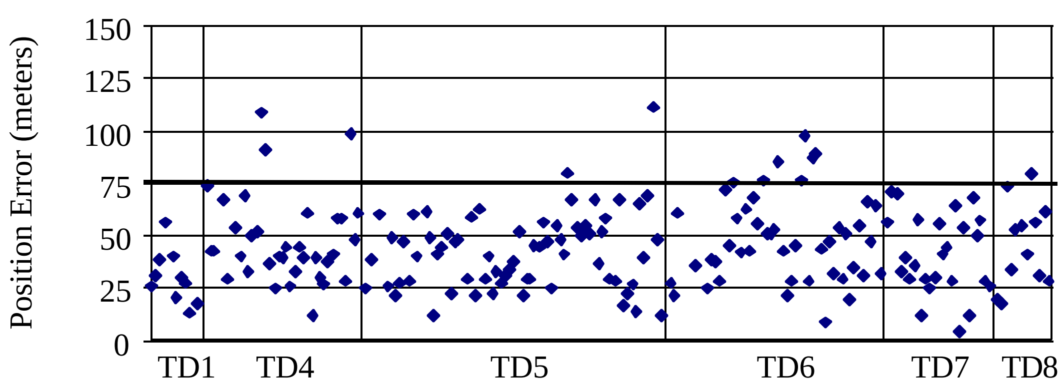

Figure 5. TDRS 42-Hour Postmaneuver Errors With Current Procedures

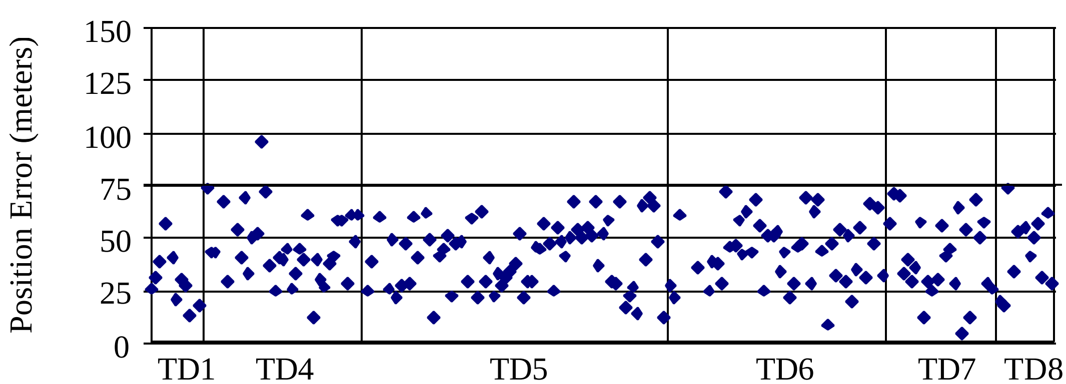

Figure 6. TDRS ~20- to 42-Hour Postmaneuver Errors With Current Procedures

plane analysis (Reference 3). Of the 195 cases, 93.3 percent would have met Terra's requirement for 42 hours.

Terra's operational requirement is that the 75–meter accuracy should be met until 2100 GMT on the next day at the 3σ–level, which is 99.73 percent of the cases. Using the current procedures, the FDF met this 75–meter requirement in 99.5 percent of the cases since February 1998. The one case (TDRS−4) that exceeded the 75–meter limit for the operational Terra span did so 33 hours after the maneuver. Because of this failure to meet the requirement, an intermediate postmaneuver update should be considered for TDRS−4.

Since the original constrained plane analysis, plane constraints have been tightened for all TDRSs to provide accuracy improvements. The TDRSs with the lowest orbital inclinations benefited the most from additional tightening of plane constraints.

Tuned data weights gave good results with TDRS−5 solutions that had unusually large solution noise. Some TDRS−5 solutions had poor use of Doppler data unless data weights or the σ–multiplier were changed.

We conclude that the tailored tracking data technique helps to improve 4–hour solution accuracy, as do plane constraints, optimal range biases averaged over several maneuvers, and, in cases of large solution noise, tuned data weights.

Modeling enhancements for spacecraft area and for handling of different antenna biases are expected to further improve the postmaneuver solution accuracy results.

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